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1. REPORT DATE (DD-MM-YYYY) 07-06-2010		2. REPORT TYPE Conference Proceeding		3. DATES COVERED (From - To) 2009-2010	
4. TITLE AND SUBTITLE High Actuator Count MEMS Deformable Mirrors for Space Telescopes				5a. CONTRACT NUMBER NNX10CE09P, NNX10CE08P	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Steven Cornelissen, Jason Stewart, and Tom Bifano				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Boston Micromachines Corporation 30 Spinelli Place Cambridge, MA 02138				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) NASA Goddard Space Flight Center				10. SPONSOR/MONITOR'S ACRONYM(S) NASA GSFC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES Presented at Mirror Technology Days, Boulder, Colorado, USA, 7-9 June 2010.					
14. ABSTRACT Micro Electro Mechanical Systems (MEMS) deformable mirrors are capable of correcting aberrations in space-based optical imaging systems. The small size, weight, and power requirements are ideal for space based adaptive optics. However, the yield, number of actuators, and surface accuracies can be improved. Yield is the proportion of the mirror segments that work. A low-power driver is also needed. The impact of microscopic manufacturing defects and substrate bowing were investigated. To reduce power consumption in the drive electronics, a multiplexed driver was investigated. A prototype of the multiplexed driver was constructed and will be used for future tests on a deformable mirror.					
15. SUBJECT TERMS MEMS, Deformable Mirror, Driver, Optics, Aberration, Adaptive, Substrate, Bowing					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 22	19a. NAME OF RESPONSIBLE PERSON Hans-Peter Dumm
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code) 505-853-8397

High Actuator Count MEMS Deformable Mirrors for Space Telescope

*11th Annual Mirror
Technology Days*

June 7th, 2010



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NASA SBIR PHASE I

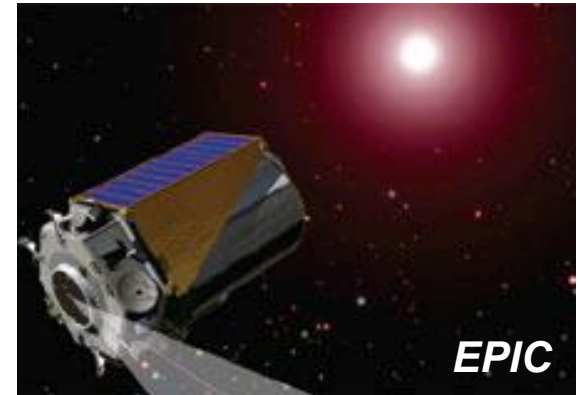
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Outline

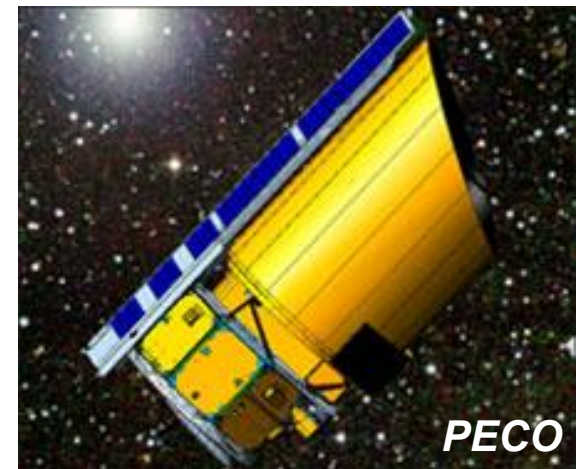
- MEMS DM Space telescopes applications
- Background on MEMS DMs
 - Architecture
 - Performance
- 1027 TTP device
 - 331 element DM
 - Yield
 - Surface Figure
- Multiplexing drive electronics
 - Description of current electronics
 - New Multiplexing drive electronics development

Applications for MEMS DMs in Space Telescopes

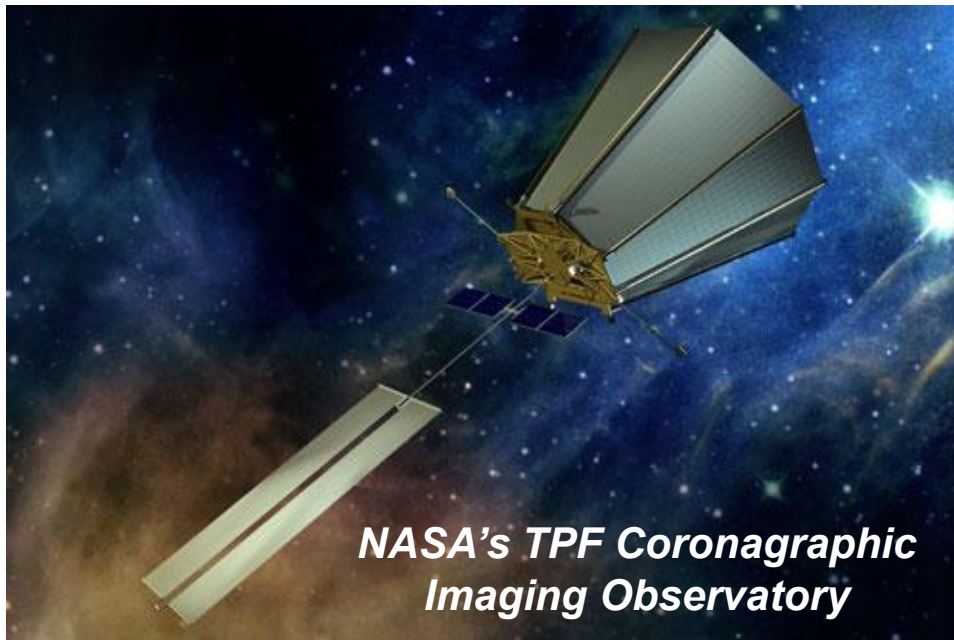
- Correction of static and slow moving (thermal) aberrations in space-based optical imaging systems
 - Astronomy – Direct Planet Detection
 - High Contrast Imaging
 - Astronomy/Reconnaissance
 - Correction of surface figure errors in Light weight primary mirrors



Extrasolar Planetary Imaging Coronagraph



Pupil-mapping Exoplanet Coronagraphic Observer



Why MEMS for DMs?

Design

Smaller size/weight/power needed for space-based AO

Inherently scalable to larger arrays (~**4000**) needed for large telescope AO

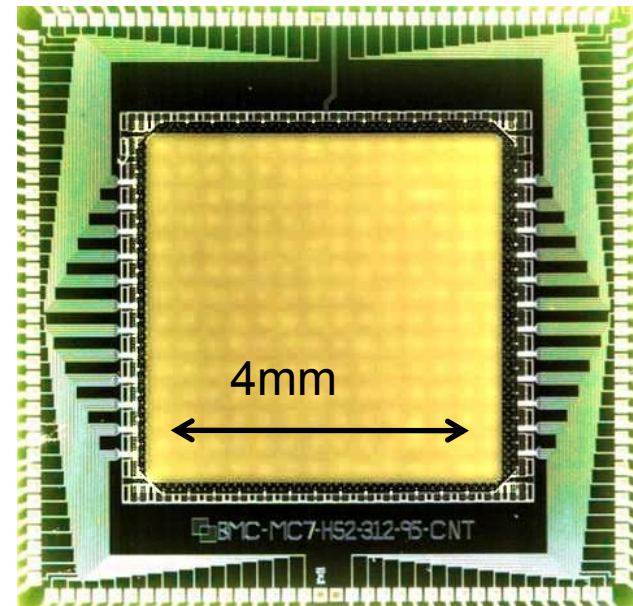
Manufacturability

10x Lower cost (~\$**150/actuator**) than macroscale devices

Batch produced (vs. manual assembly)

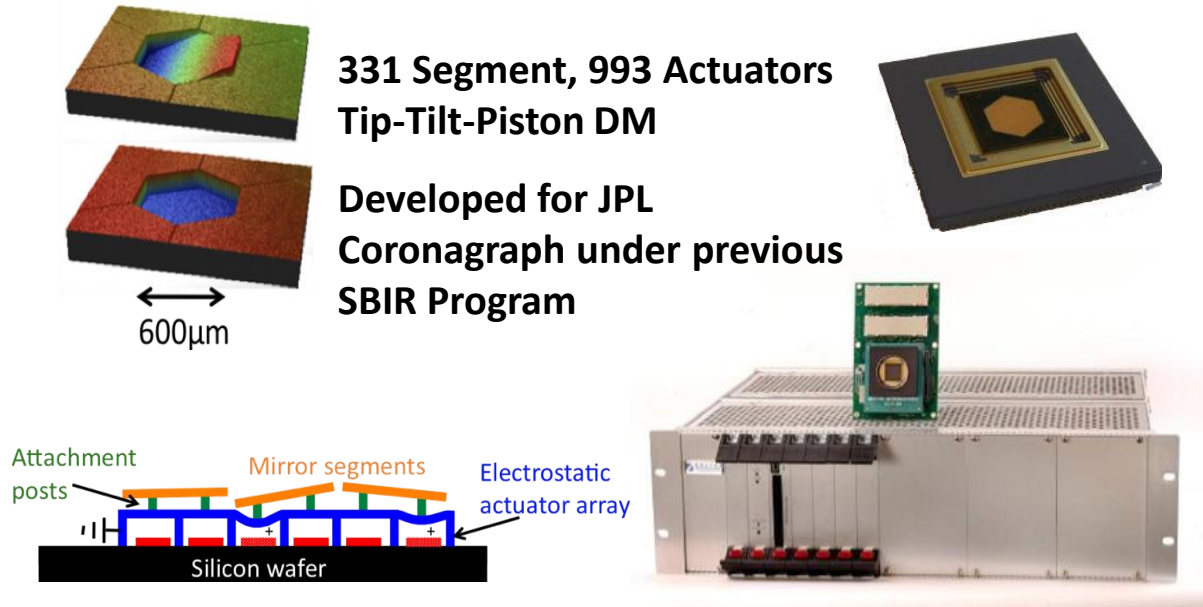
Performance

- No hysteresis
- Reliable
- Fast
- Predictable
- Polarization and wavelength insensitive



The advantages of these MEMS DMs have inspired a new generation of imaging instruments, and laser beam control systems

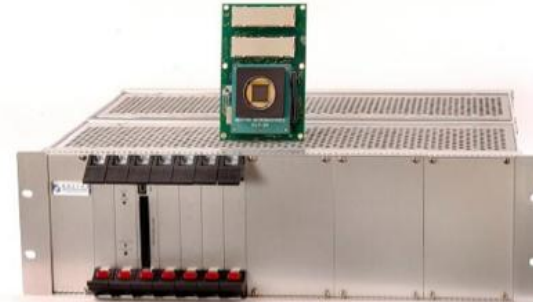
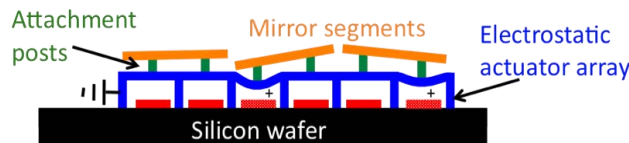
NASA SBIR Programs



331 Segment, 993 Actuators
Tip-Tilt-Piston DM

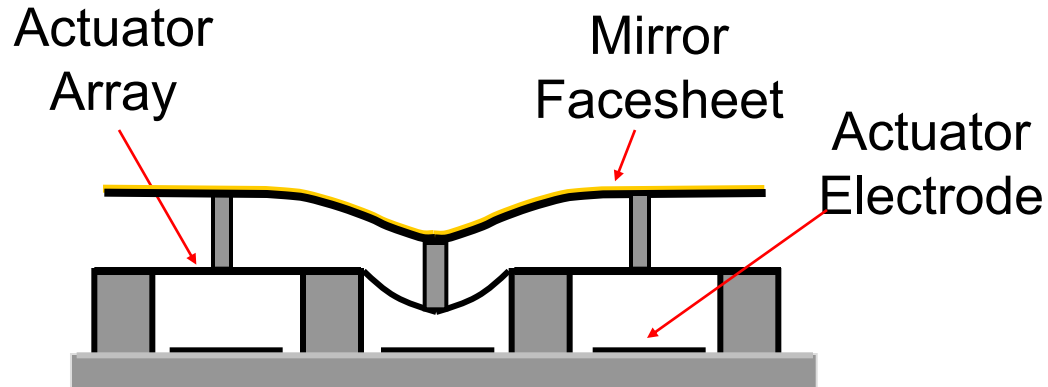
Developed for JPL
Coronagraph under previous
SBIR Program

600 μm



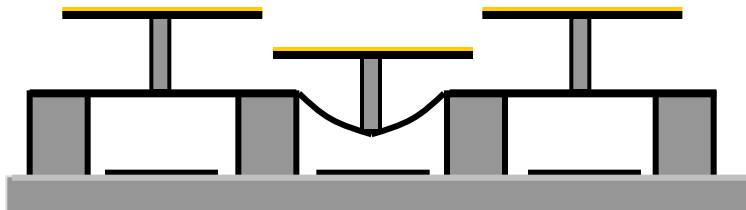
- **Enhanced Fabrication Processes Development for High Actuator Count Deformable Mirrors (Phase I, Contract #NNX10CE09P)**
 - **Objective:** Advance manufacturing science and technology to improve yield and optical surface figure in large, high-actuator count, high-resolution deformable mirrors required for wavefront control in space-based high contrast imaging instruments (target: 3081 actuator, 1027 segment tip/tilt/piston DM)
- **Compact Low-Power Driver for Deformable Mirror Systems (Phase I, Contract #NNX10CE08P)**
 - **Objective:** develop an ultra-low-power multiplexed electronic driver for high-resolution deformable mirror systems

BMC MEMS DM Architecture



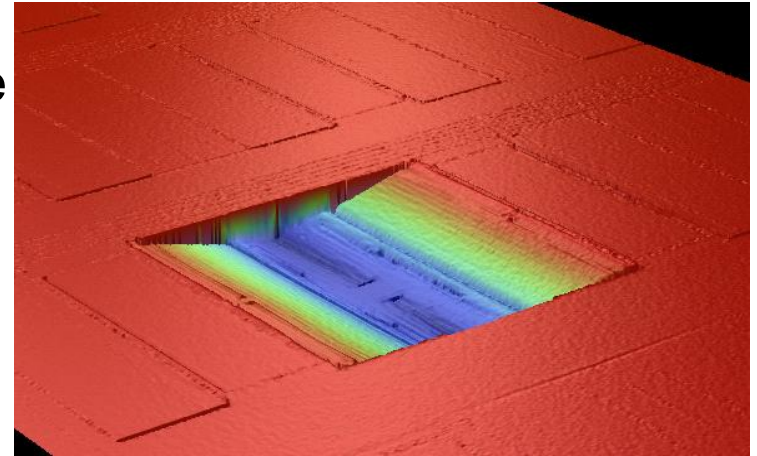
Continuous mirror (smooth phase control)

- Localized Influence Function
- Hysteresis-Free
- Scalable Architecture

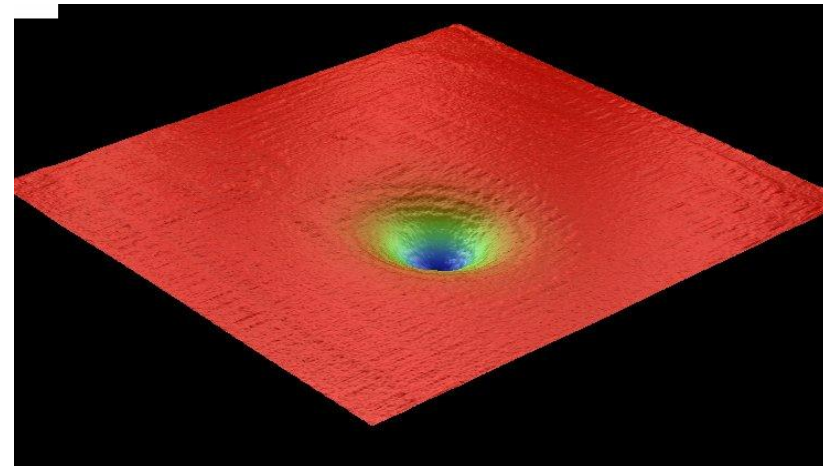


Segmented mirror (uncoupled control)

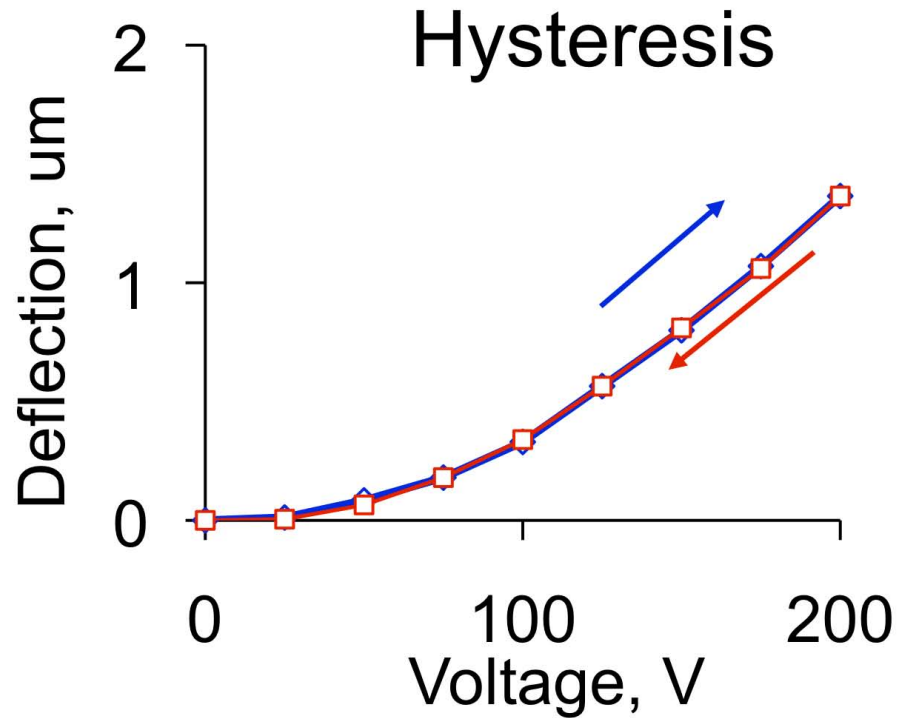
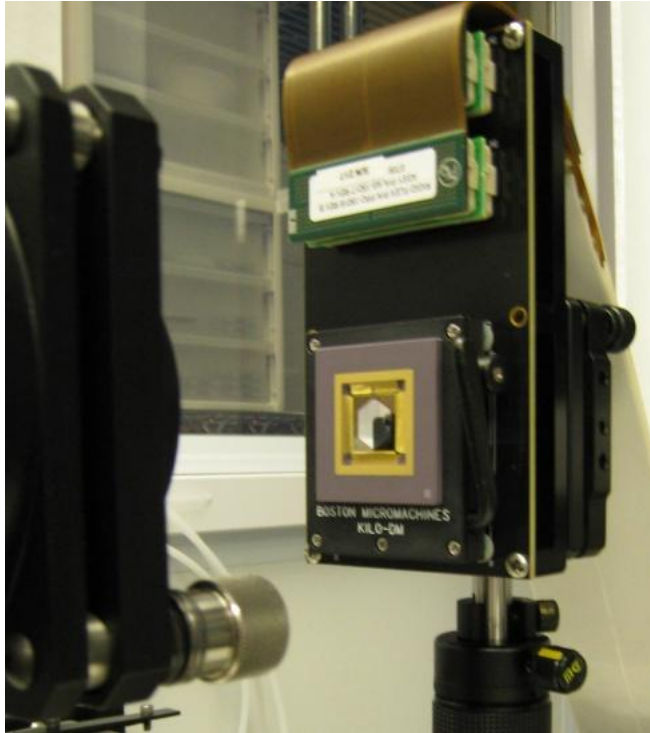
Deflected Actuator



Deformed Mirror Membrane

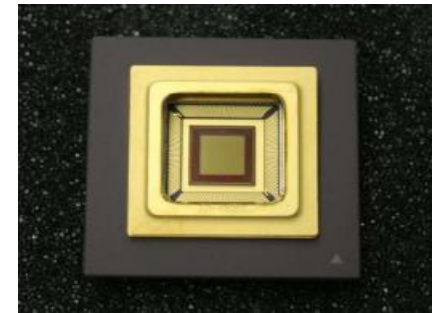
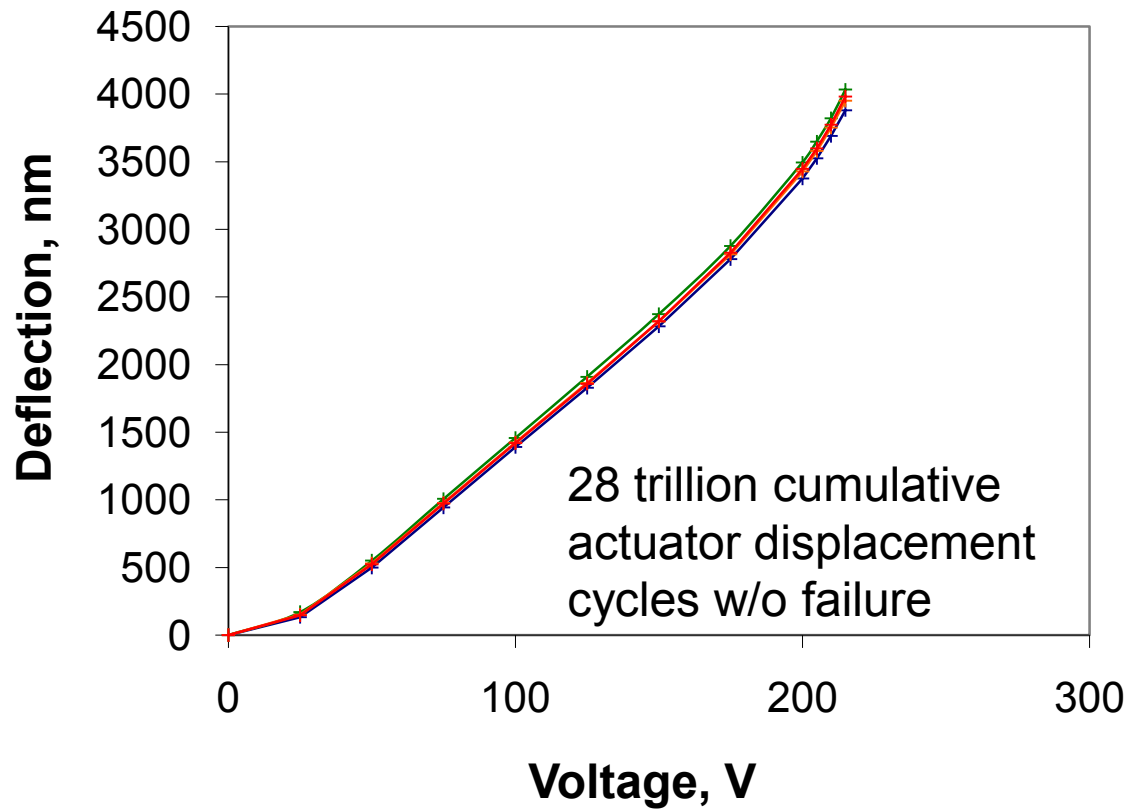


MEMS DMs exhibit no hysteresis

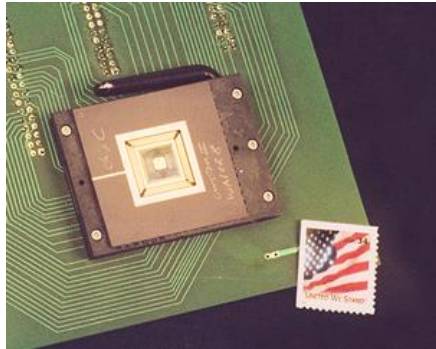


MEMS DMs Reliable

Deflection measured periodically
in DM lifetime test



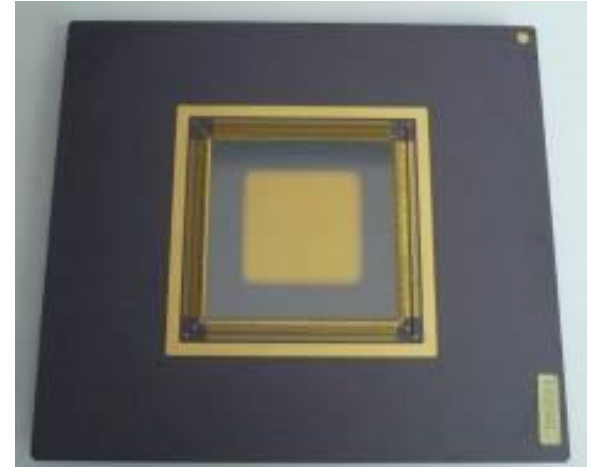
Evolution of BMC MEMS DMs



Y2000
2 μ m stroke
(140 actuators)

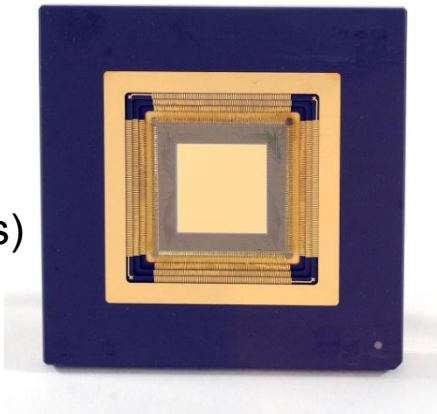


4 μ m stroke – Y'04
6 μ m stroke – Y'07
(140 actuators)

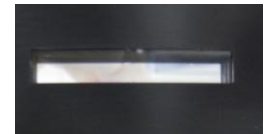
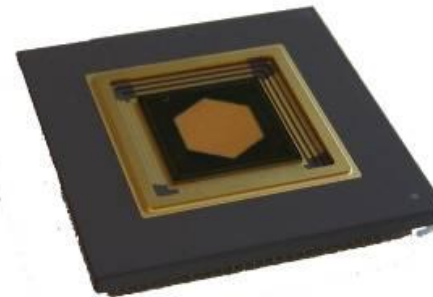


Y'10
4 μ m stroke
(4092 actuators)

Y'03
2 μ m stroke
(1020 actuators)
NASA SBIR



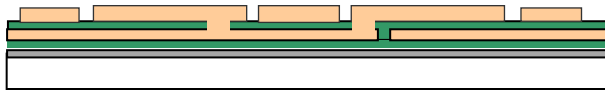
Y'08
2 μ m stroke/6mrad Tip & Tilt
(993 Actuators)
NASA SBIR



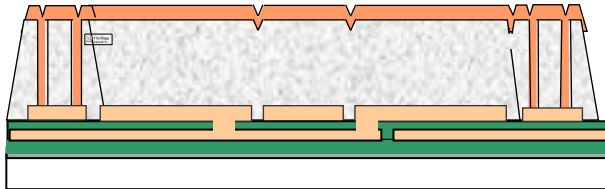
Y'09
2 μ m stroke 1-D Array
(1x140 act.)

MEMS DM Fabrication Process

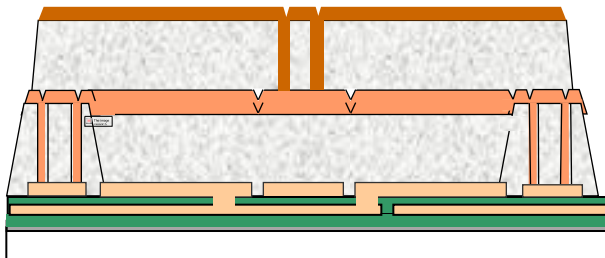
(deposit, pattern, etch, repeat)



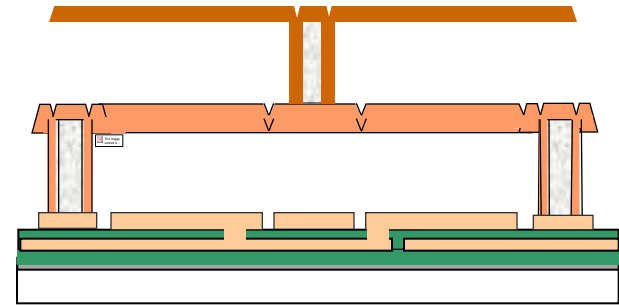
Electrodes & wire traces:
polysilicon (conductor) & silicon nitride (insulator)



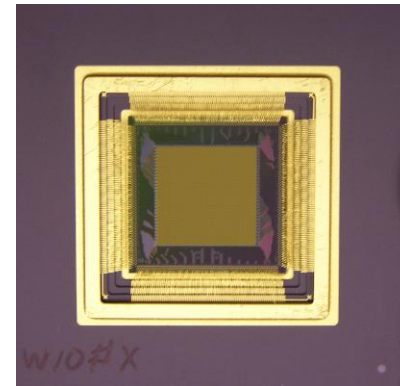
Actuator array:
oxide (sacrificial spacer) and polysilicon (actuator structure)



Mirror membrane:
oxide (spacer) and polysilicon (mirror)



MEMS DM:
Etch away sacrificial oxides in HF, and
deposit reflective coating

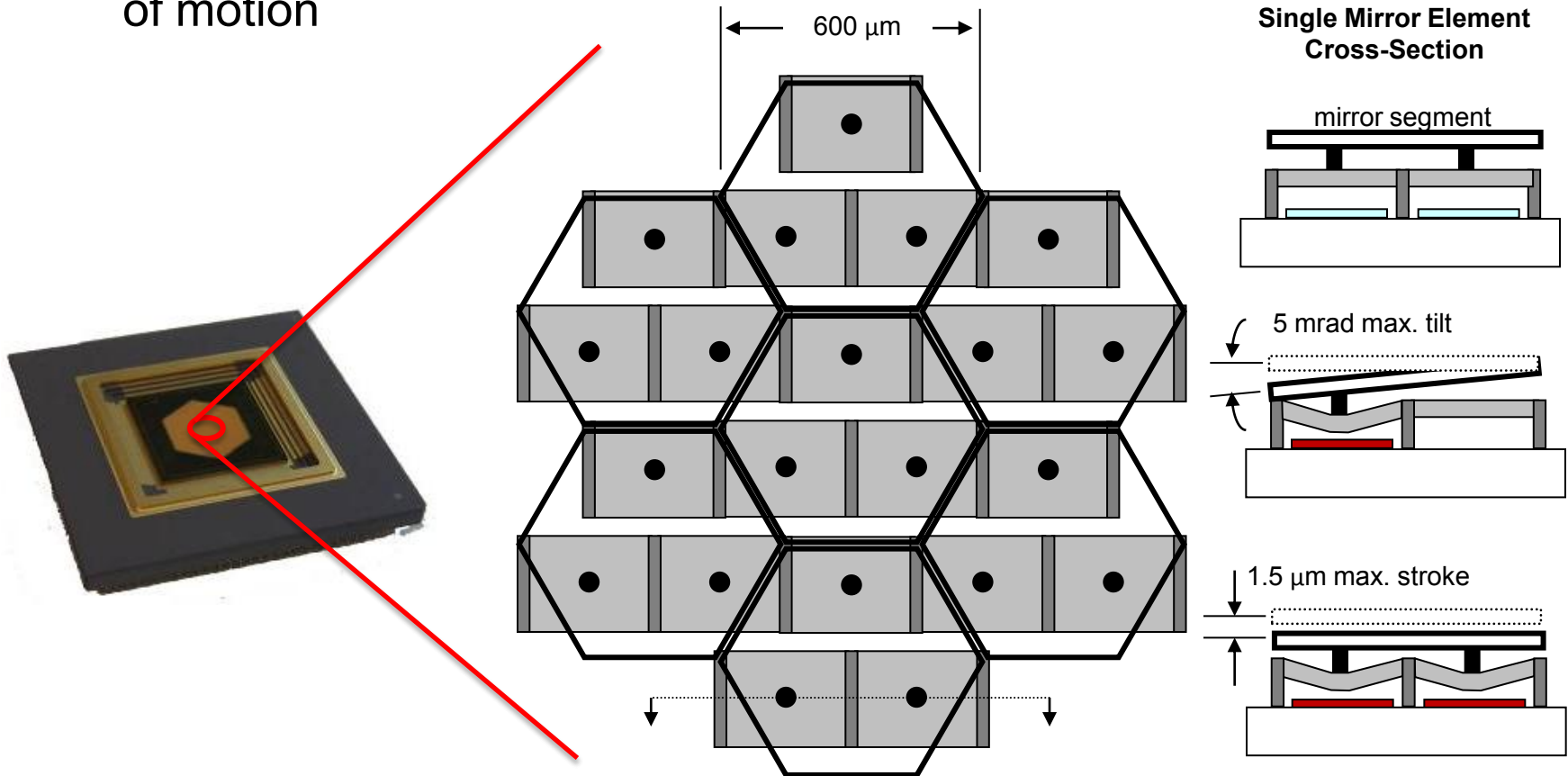


Electrical Interconnects:
Die attach and wirebond to ceramic
chip carrier

Batch fabrication: 20 wafers per batch, 3-100 devices/wafer (depending on die size)

Tip-Tilt-Piston DM Overview

- Application: *Visible Nulling Coronagraph*
 - DM provides instrument with phase control using piston motion and amplitude control using tip-tilt motion
- Tip-tilt-piston degrees of freedom provided by three piston-only electrostatic actuators
- <10nm RMS mirror segment flatness achieved throughout full range of motion



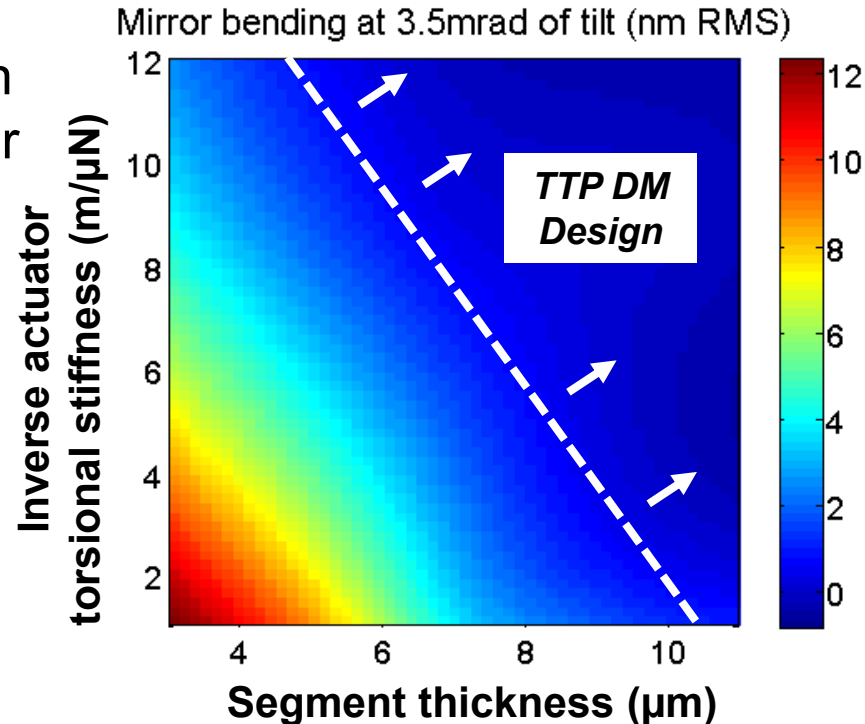
Fabrication of Ultra-Flat MEMS DMs

Challenges:

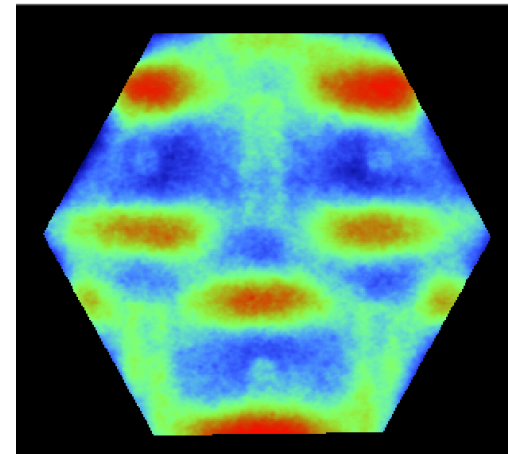
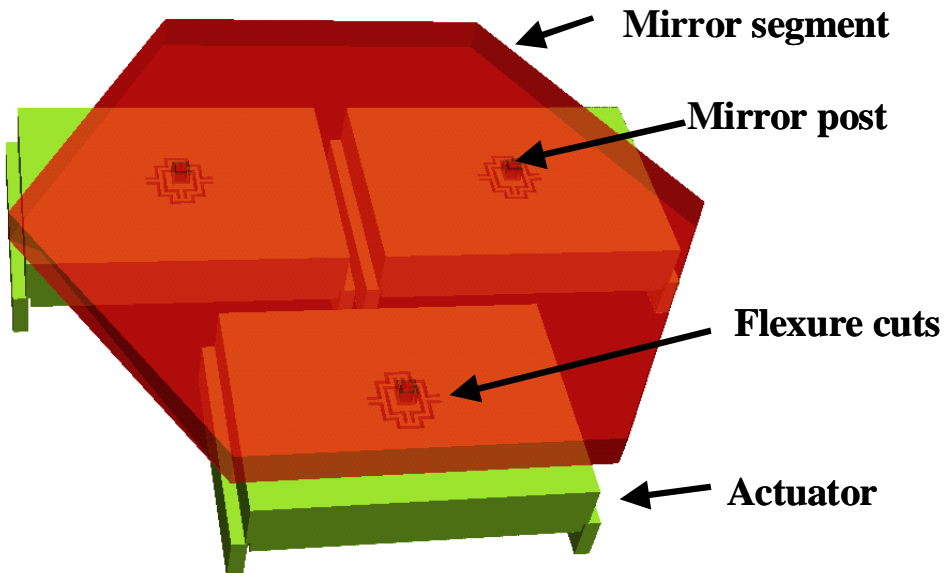
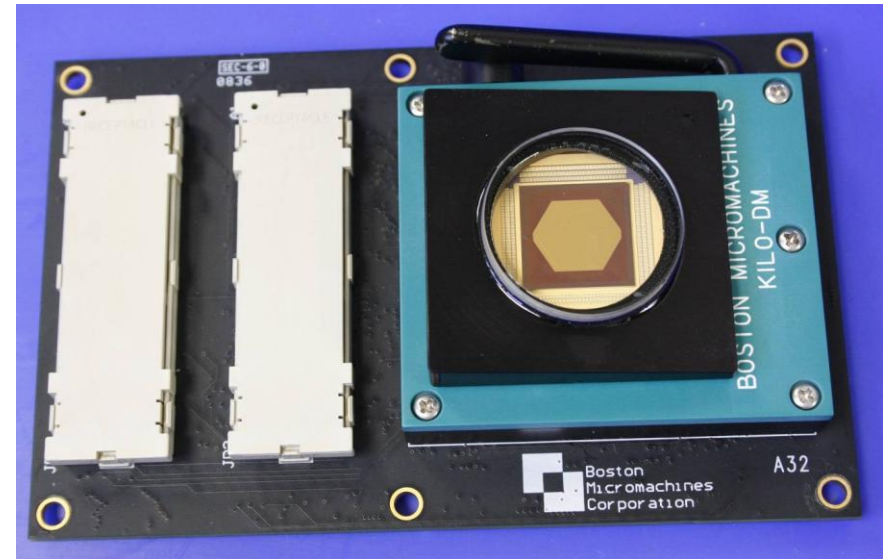
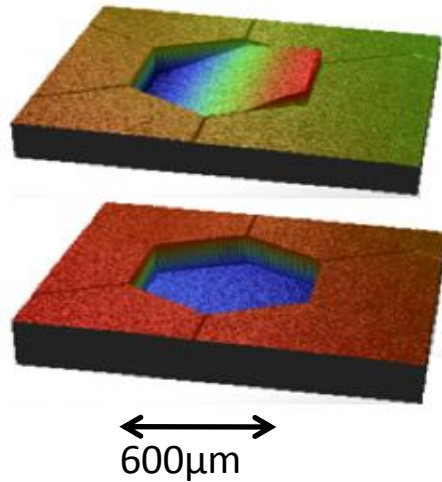
1. Mirror segments **bend** during actuation due applied moments from the actuator post connections
2. Mirror segments **curl** after release due to embedded stress gradients in the polysilicon layer
3. Optical quality is reduced by **print-through** of underlying layers

Solutions:

1. Bending-
 - a) **Resist** applied bending moments => increase rigidity with mirror thickness
 - b) **Reduce** applied bending moments => decrease actuator torsional stiffness
2. Counteract residual stress gradients through anneals of mirror polysilicon
3. Deposit thicker polysilicon for additional polishing to reduce print-through



331 segment TTP MEMS DM

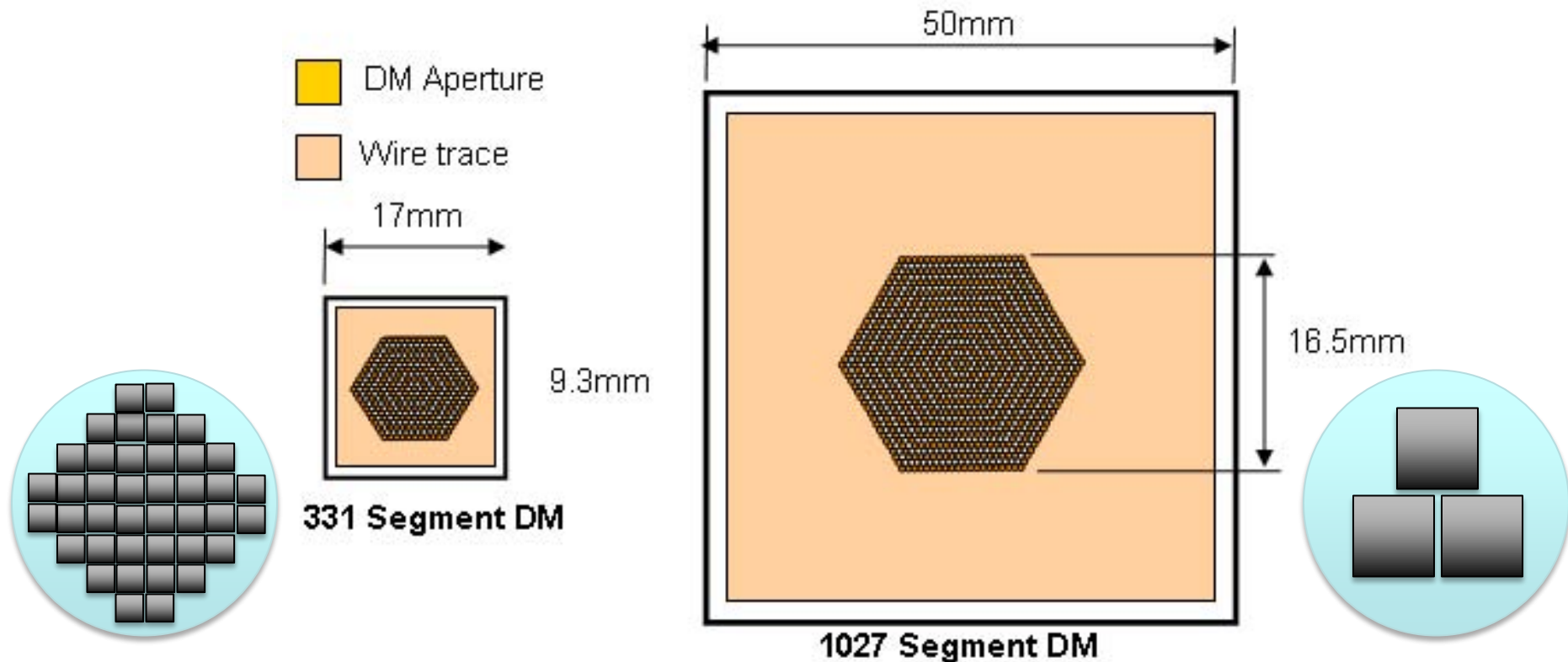


6nm RMS
over
600μm
segment

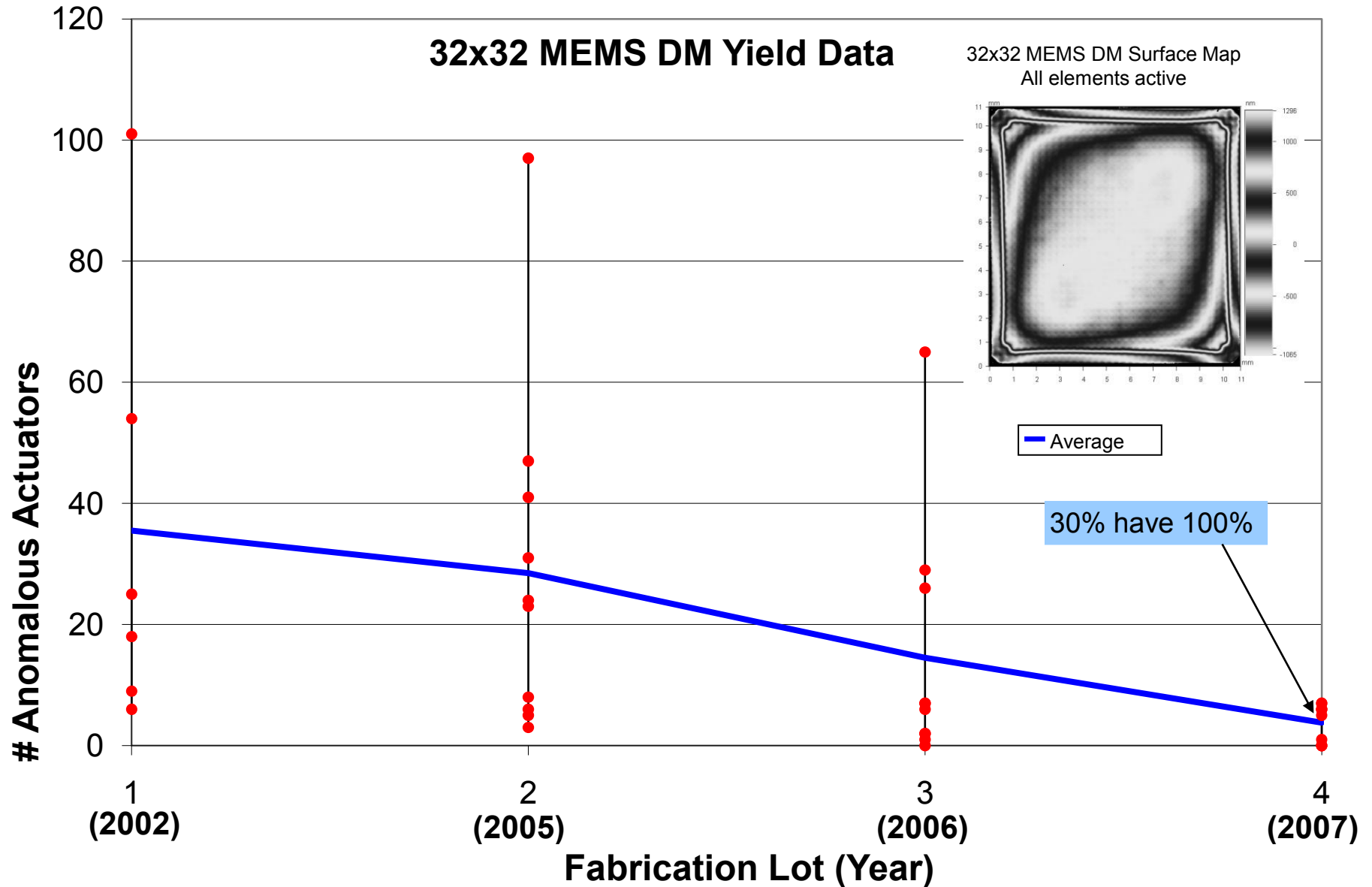
Delivered to NASA, (JPL HCIT) 2008

1027 Element Tip-Tilt-Piston MEMS DM

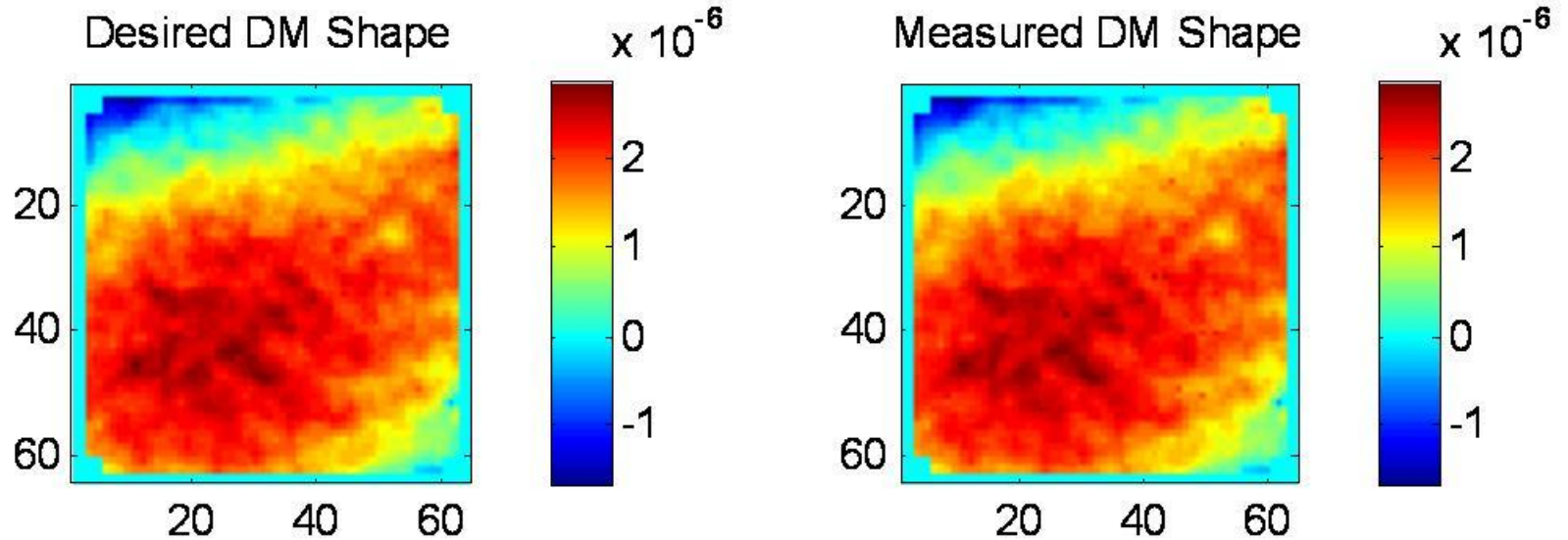
- Scale up mirror segments/actuators from 331/993 to 1027/3081
- Device architecture and fabrication process fundamentally scalable
- Challenge:
 - Managing inherent microscopic manufacturing defects (function of die area)
 - Controlling surface figure errors resulting from substrate bow and polishing



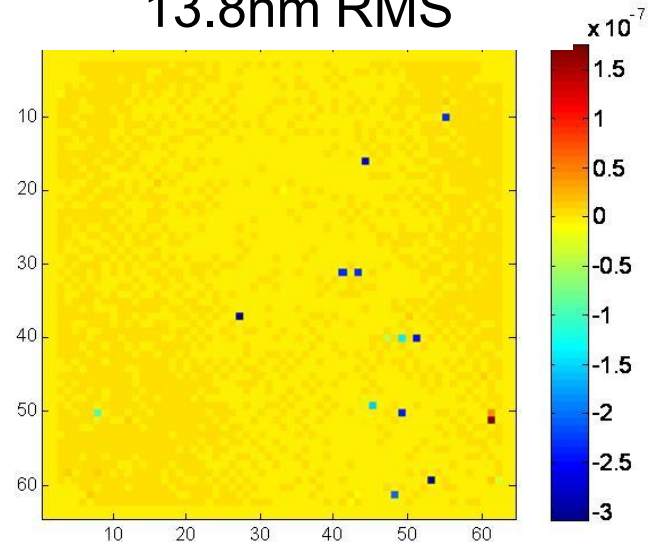
DM Actuator Yield



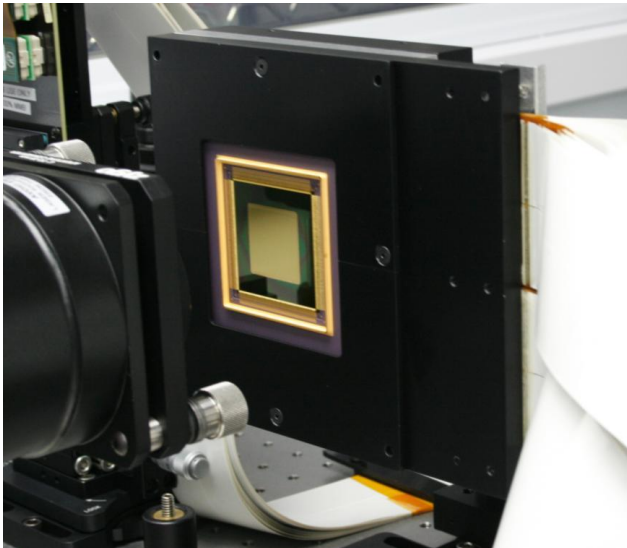
4092 Element DM Actuator Yield



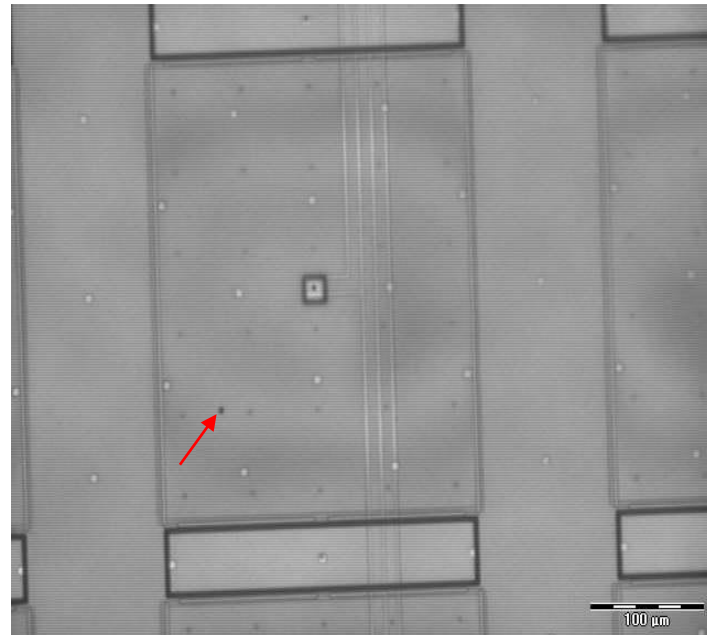
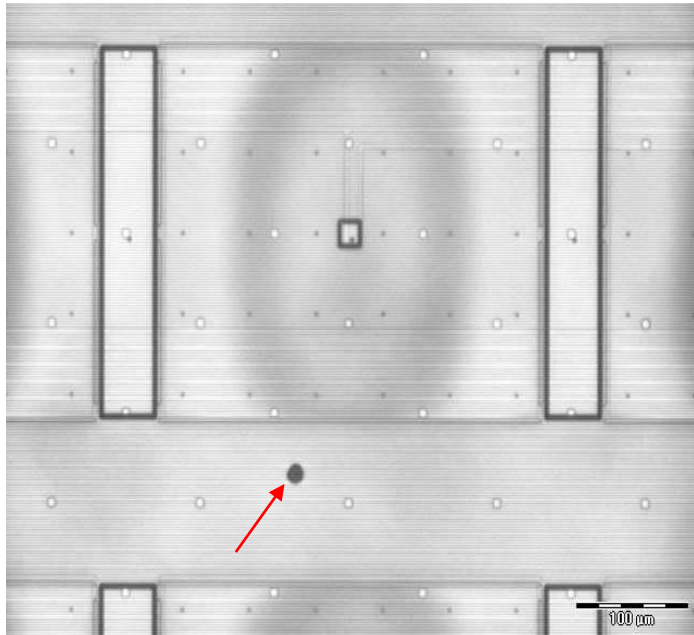
Residual Error:
13.8nm RMS



DM Actuator Yield :
>99.4%



Fabrication Process Defect Related Yield Issues



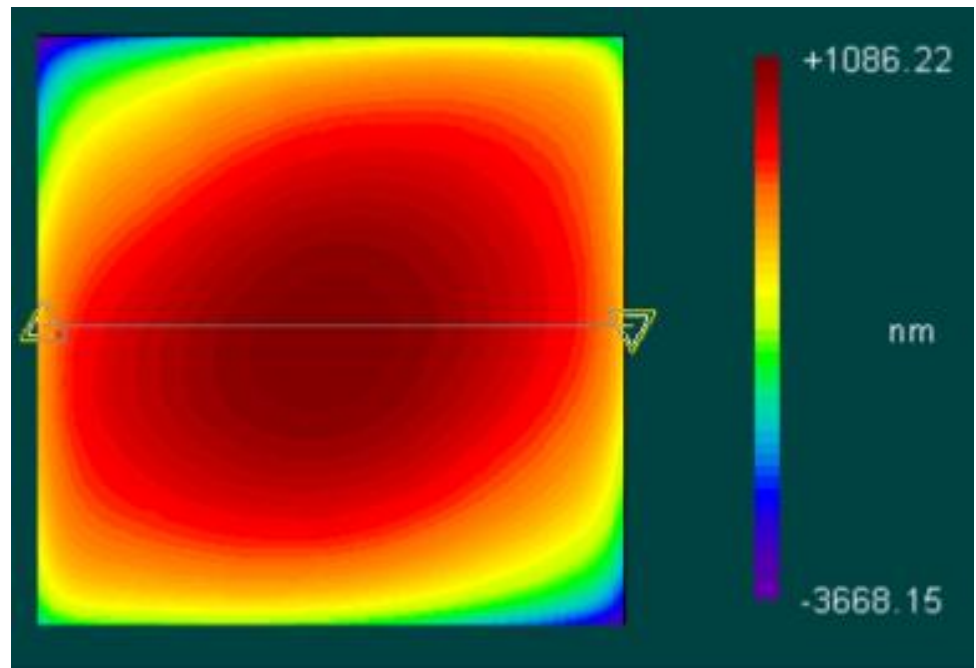
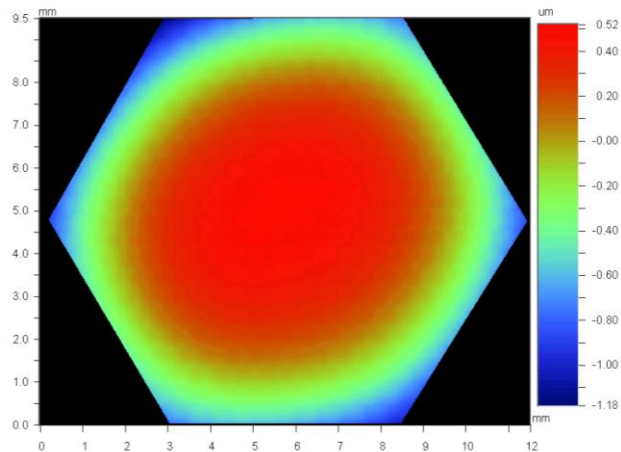
- Microscopic embedded particles are introduced during material deposition processes
 - electrical shorts (inactive/coupled actuators)
 - Surface figure defects
- Enhanced fabrication methods and design changes investigated in SBIR program to mitigate defect count and effects

DM Surface Figure

- Surface Micromachined devices conform to substrate figure
 - Imbalance of front and backside film thickness results on wafer bow
 - Wafer bow of 50m ROC typical at end of manufacturing process
- New thin film deposition processes being developed to reduce wafer bow to 300m ROC

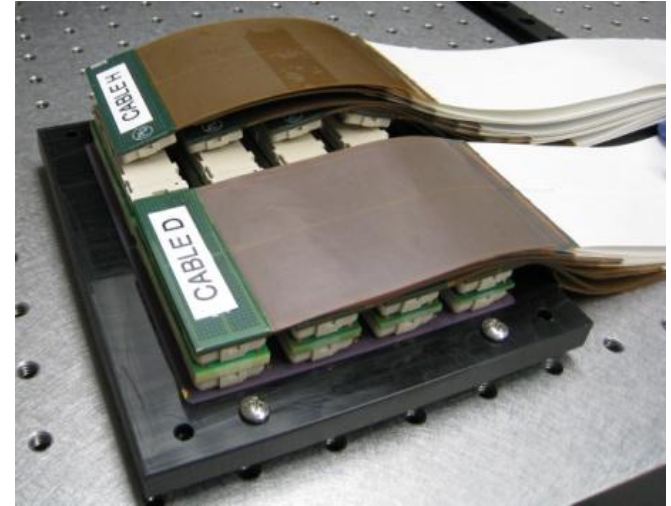
4096 element DM Active Aperture
Figure Error (P-V): $\sim 3.5\mu\text{m}$

331 element DM Active Aperture
figure error (P-V): $\sim 1\mu\text{m}$



DM Drive Electronics

- Existing DM drive electronics using single DAC and amplifiers for each DM drive channel
- MEMS DM actuator is a capacitor – most power consumed driving high voltage amplifiers & DACs
- Space-based platforms require low power, more compact, and light weight electronics



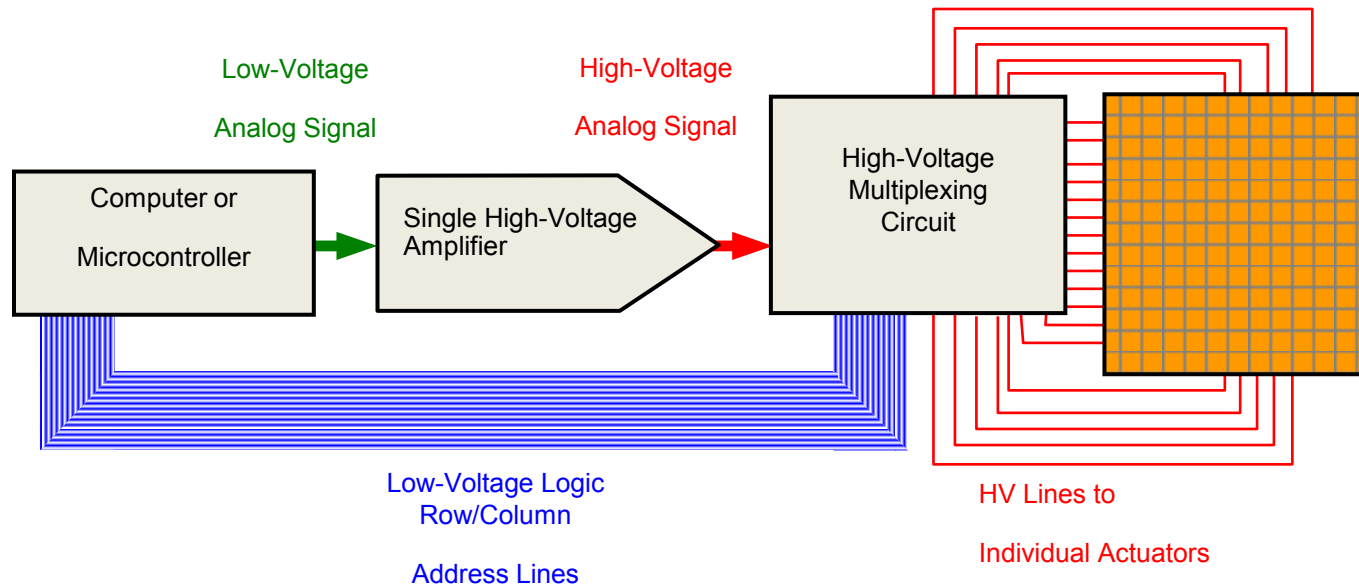
MEMS DM Driver Specification

- # Channels: 4,096 channels
- Power Consumption: 80W (typ)
- Resolution: 14-bit
- Mass (w/ cables): 13.6kg
- Max Frame Rate: 24kHz
- Size: 3U Chassis (5.25" x19" x14")

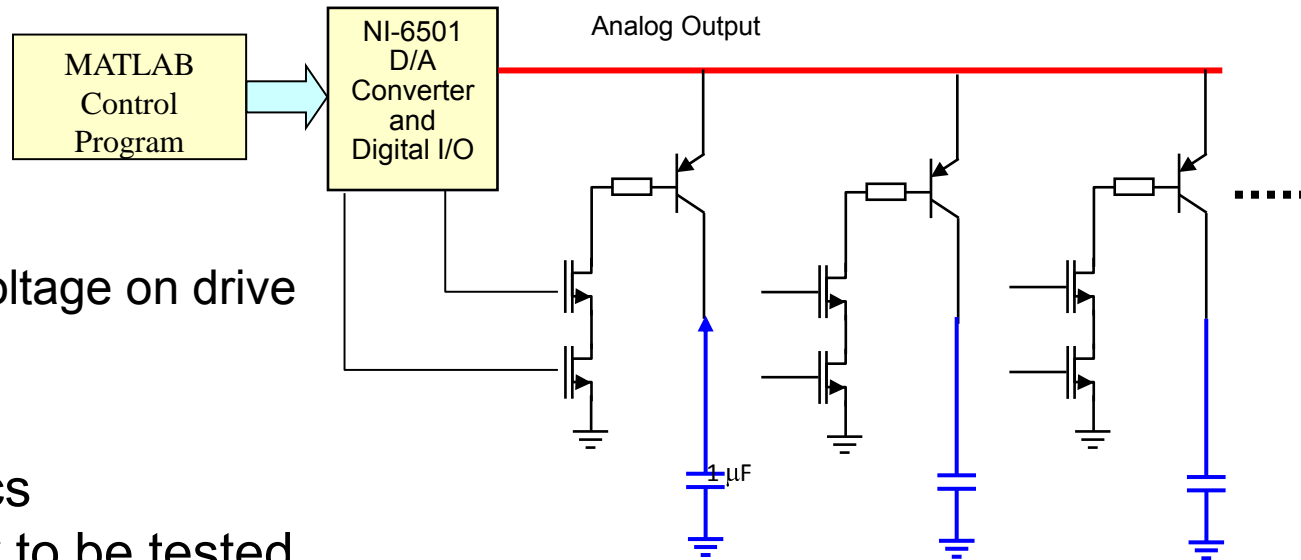


Multiplexed Drive Electronics

- Phase I SBIR aims to develop new multiplexed drive electronics
 - Reduce power by 2 orders of magnitude
 - Reduce size by order of magnitude
 - 16-bit resolution (0-300V)

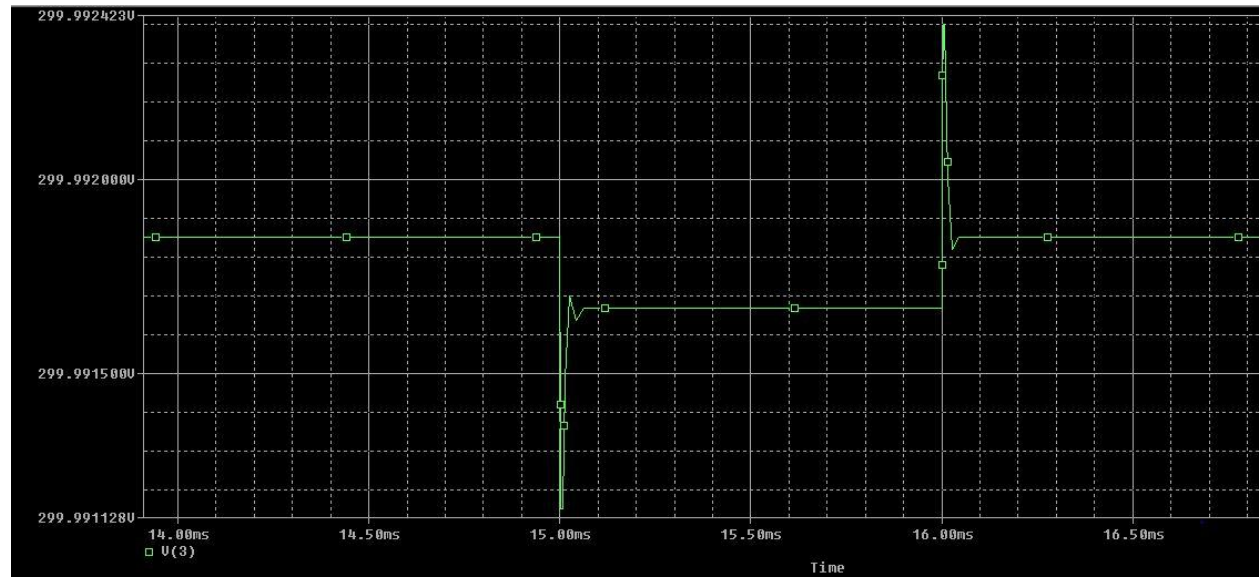


Multiplexed Drive Electronics



- Challenges:
 - Maintaining stable voltage on drive channel
 - Limit charge leakage
- Prototype of electronics constructed and ready to be tested with DM

PSPICE Simulation of single channel output



Thank You

Boston Micromachines Corporation is advancing MEMS deformable mirror technology to meet needs for spaced based Adaptive Optics systems through SBIR program

Acknowledgements

- Funding from NASA/JPL
 - SBIR Phase I # NNX10CE09P
 - SBIR Phase I # NNX10CE08P
- Mark Horenstein - Boston University Photonics Center

